

# Astrophysical S factor for $^{11}\text{C}(p, \gamma)^{12}\text{N}$ , from a measurement of $^{11}\text{C}(d, n)^{12}\text{N}$

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The first generation of stars formed after the Big Bang is believed to have included a large number of very massive stars of greater than 100 solar masses [1]. Though long dead, it is important to understand these initial stars both for their effect on the early universe through massive supernovae and nucleosynthesis and for understanding their remnants, black holes, that will still exist in the present day.

A unique feature of the first generation of stars was a complete lack of initial seed nuclei for the CNO cycle, as no elements above boron were produced in the Big Bang. The CNO cycle is a hydrogen burning chain of proton reactions on carbon, nitrogen, and oxygen isotopes that can produce vastly higher rates of energy generation in massive stars as compared to the alternate p-p chain, which is limited by the slow rate of the weak-force-reaction  $p + p \rightarrow d + e^+ + \bar{\nu}$ . Massive and rapid energy generation is needed to stabilize a very large star against collapse, or even just to slow the process. Just slowing the infall can be significant, as a coalescing massive gas cloud can build up sufficient kinetic energy that the onset of helium burning, through the “triple alpha” reaction, can be too late to prevent total collapse to a black hole, with no resulting stellar explosion or nucleosynthesis [2]. Even in models of stars that can stabilize against collapse (due to rotation or smaller size) a relatively small amount of CNO nuclei, leading to higher energy generation in a hydrogen-burning envelope, can have large effects on later evolution, such as by inducing convective mixing that dredges up the products of helium burning [1].

Thus, it is important for our understanding of the first generation of stars to determine processes by which even small amounts of CNO nuclei might be produced during hot hydrogen burning, well before the onset of helium burning. These “hot proton-proton” chains were investigated in Ref. 3. The main impediments blocking production of CNO nuclei during hydrogen burning are the low alpha-particle emission thresholds of  $^8\text{B}$  and  $^{12}\text{C}$ , leading to recycling through the reactions  $^7\text{Li} + p \rightarrow 2^4\text{He}$  and  $^{11}\text{B} + p \rightarrow 3^4\text{He}$ . These obstacles can be jumped through capture of an alpha particle on one of the isotopes produced in side chains of p-p burning:  $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$  or  $^8\text{B}(\alpha, p)^{11}\text{C}$ . The produced  $^{11}\text{C}$  can then capture a proton to produce  $^{12}\text{N}$ , which quickly decays to  $^{12}\text{C}$  and begins the CNO cycle. Of course,  $^{11}\text{C}(p, \gamma)^{12}\text{N}$  is in competition with the decay of  $^{11}\text{C}$  ( $t_{1/2}=20$  min) to  $^{11}\text{B}$ , followed by  $^{11}\text{B}(p, 3^4\text{He})$ . Thus, one wishes to measure reactions that create and destroy  $^7\text{Be}$ ,  $^8\text{B}$ , and  $^{11}\text{C}$  (also  $^9\text{C}$ , due to a possible side chain  $^8\text{B}(p, \gamma)^9\text{C}(\alpha, p)^{12}\text{N}$ ).

Recently, the method of asymptotic normalization coefficients (ANC) has been used to estimate the  $^{11}\text{C}(p, \gamma)$  cross section. A group from Texas A&M, which pioneered the ANC technique, measured the reaction  $^{14}\text{N}(^{11}\text{C}, ^{12}\text{N})^{13}\text{C}$  using a  $^{11}\text{C}$  beam produced in-flight [4]. The peripheral nature of the proton transfer is what allows this reaction to be related

to  $^{11}\text{C}(p, \gamma)^{12}\text{N}$ ; their measurement appears to determine the S-factor for the latter reaction to plus or minus 15% over the relevant energy range. However, to be reliable, the ANC technique must give consistent answers from alternate transfer reactions, and a Chinese group has performed a complementary measurement of  $^{11}\text{C}(d, n)^{12}\text{N}$  [5]. Their results for the ANC and S-factor are higher than the Texas A&M numbers by about 50%, though this is only slightly more than one error bar. The ANC’s measured by the two groups were  $1.73 \pm 0.25 \text{ fm}^{-1}$  [4] and  $2.86 \pm 0.91 \text{ fm}^{-1}$  [5].

The limiting feature of the Chinese experiment was very low statistics; the number of  $^{11}\text{C}$  projectiles on target was less than  $2 \times 10^8$ , total. This is less than 10 seconds of  $^{11}\text{C}$  beam from BEARS.

Fig. 1 shows a spectrum taken during a test run with the BEARS  $^{11}\text{C}$  beam, a  $(\text{CD}_2)_n$  target, and a simple detector telescope. Our spectrum is considerably cleaner than in Ref. 5, the  $^{12}\text{N}$  peak has much better resolution, and even in this short run statistics are considerably higher.

Thus we are measuring  $^{11}\text{C}(d, n)^{12}\text{N}$  with both improved statistics and systematics, to yield a measurement of the  $^{12}\text{N} \rightarrow ^{11}\text{C} + p$  asymptotic normalization coefficient to a similar accuracy as the Texas A&M result, allowing a strong test of the consistency of the ANC method for determining  $^{11}\text{C}(p, \gamma)^{12}\text{N}$ .

## REFERENCES

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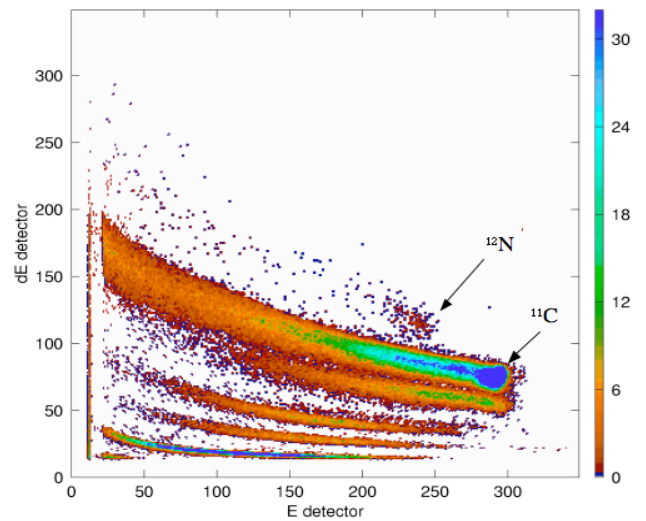


FIG. 1: 150 MeV  $^{11}\text{C}$ , 72  $\mu\text{m}$   $\square\text{E}$  detector,  $\square_{\text{lab}}=2.7^\circ$ .